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MIXING AND COMBUSTION MECHANISMS IN HIGH-SPEED FLOWS.(U)
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MIXING AND COMBUSTION MECHANISMS IN HIGH SPEED FLOWS

AFOSR Contract F44620-75-C-0065

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INTRODUCTION

Although a considerable amount of research effort has been devoted to the development of techniques for the prediction of reacting flow fields, the design and development of advanced propulsion systems remains heavily dependent on cut-and-try methods. This approach to the development of new systems is not only excessively expensive, but also, as historical evidence shows, it does not provide the means to extrapolate particular design rules to the next generation of propulsion systems.

The problems inherent with cut-and-try methods are especially acute in the case of sudden-expansion (or dump) combustors in which large-scale recirculation zones exist. Such devices have, in addition to the problems involved in the coupling of the turbulent mixing and reaction kinetics common to all combustor concepts, additional problems in ignition, flame stabilization and combustion instabilities, all of which must be understood in order to support engineering design judgments.

In order to assess the current ability within the combustion community to define, analytically and experimentally, reacting flow with recirculation zones, a series of workshops have

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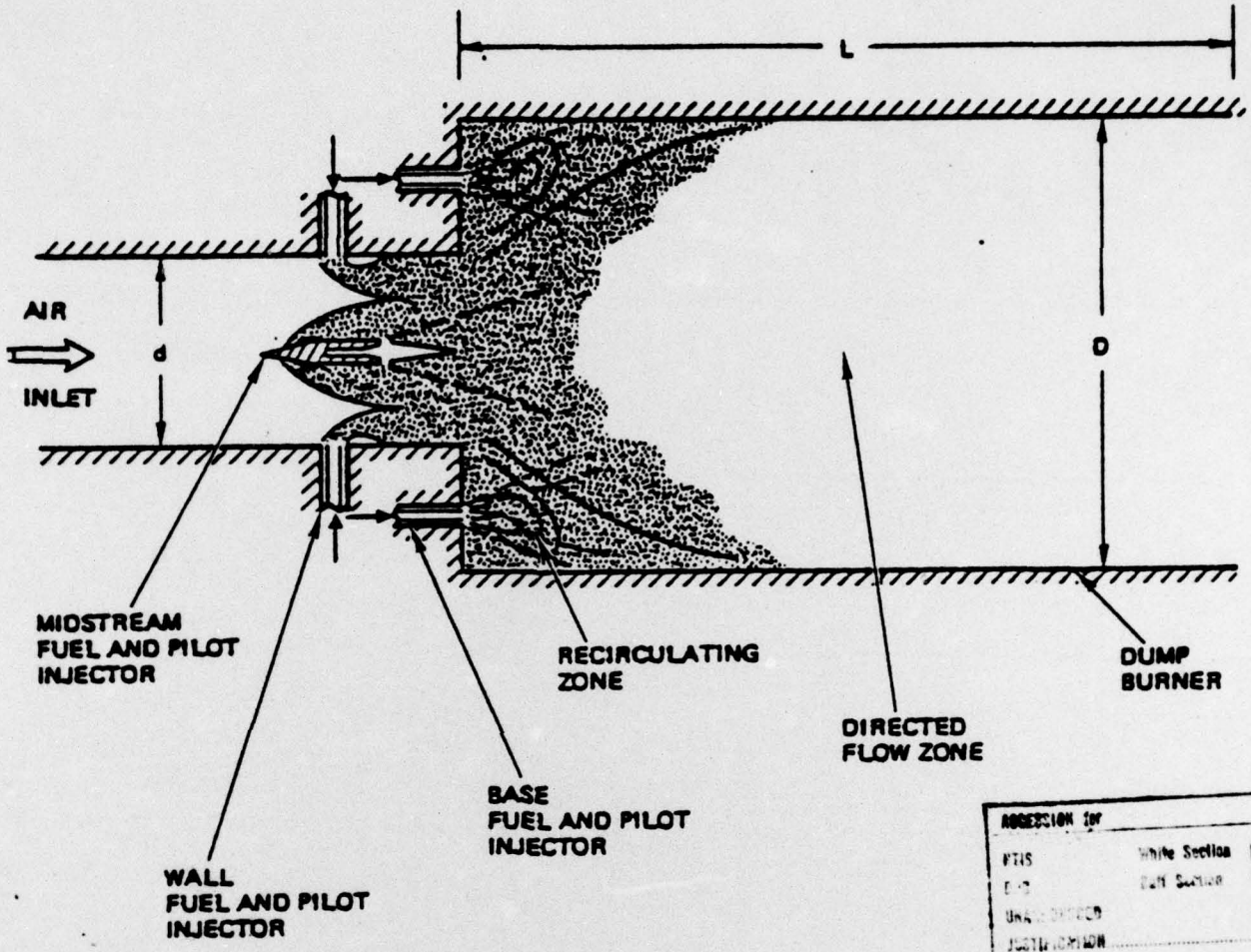
been held under the JANNAF air-breathing combustion working group. A workshop concerned with the modeling of such flows was held at the Jet Propulsion Laboratory, 9 and 10 September 1974; a companion workshop on experimental investigations of such flows was held at the Naval War College, 11 and 12 August 1975. The conclusion reached at the modeling workshop is that significantly more effort in the development of numerical methods is required before predictions of the details of reacting elliptic flows such as are involved in the dump combustor will be made. Thus, a near term methodology involving a "modular" concept should be developed to parametrically analyze the dump combustor flow field.

At the workshop on experimental investigations of dump combustors it was argued that a clear need exists for detailed experimental data on dump combustor flow fields, involving radial and axial surveys of velocity, concentration and temperature distributions as well as axial wall static pressure distributions. Further, experiments using hydrogen and air as the reactants and gaseous hydrocarbon fuels should be carried out to aid in the development of analytical models for dump combustors.

The work summarized in this report is aimed at the development of a modular techniques for the prediction of dump combustor flow fields. In the modular concept, a parabolic treatment of the directed flow portion of the flow field (see Figure 1) is coupled to a model of the recirculation zones in which they are treated as perfectly stirred reactors. Coupling relations are written which supply the boundary conditions for the parabolic flow regime and define the feed rates to the perfectly stirred reactors. The shape of the dividing streamline is assumed a priori. Since the flow field is in general elliptic, the modular approach is an approximation to the true flow field, and the specification of the species fluxes across the dividing



BASIC STUDIES ON DUMP BURNER PROCESSES:

- AIR INLET STATE
- FUEL AND PILOT INJECTION CONFIGURATIONS
- RECIRCULATION ZONE AND BURNER GEOMETRY
- MIXING PROCESSES
- KINETICS
- MULTIPHASE (HETEROGENEOUS) PROCESSES
- RESIDENCE TIME

Figure 1. Schematic of Sudden Expansion (Dump) Burner

streamline must be carried out iteratively. However, the method allows the application of tested and proved flow models to the dump combustor geometry, and is capable of yielding parameteric information of interest in sudden expansion burner design.

In addition to the theoretical work that is the major focus of the present program, close interaction with the experimental program on dump combustors being carried out at the Air Force Aeropropulsion Laboratory is being maintained. As part of this interaction, and based on the requirements developed through the analytical modeling effort and from the conclusions of the JANNAF workshop on experimental investigations of dump combustors, a matrix of desirable dump combustor experiments has been developed to help guide the AFAPL experimental program.

SUMMARY OF COMPLETED WORK

The modular concept for the analysis of the dump combustor flow field has been completed and is detailed in Ref. 1. Because the modular concept involves an iterative coupling between a parabolic flow field computation and the stirred reactors which represent the recirculation zones, considerable effort during this reporting period has been put into reducing the computational time required to carry out the parabolic portion of the calculation. The parabolic calculation involves the finite difference technique developed by Boccio, Weilerstein and Edelman [2] for flows in which finite-rate hydrocarbon chemical reactions occur, and uses the turbulent kinetic energy model developed by Harsha [3] to evaluate the local turbulent shear stress. The kinetics calculations utilizes the "quasi-global" kinetics model developed by Edelman and Fortune [4] for hydrocarbon oxidation.

Although the chemical kinetics model utilized in Ref. 2 is quite accurate, it has not been optimized in order to reduce the computational time required for a given calculation. In the current program, such optimization has been carried out, using a numerical technique in which the size of the matrix involved in the kinetics calculation is automatically altered to reflect the number of active species in a given problem, and using element conservation equations to further reduce the number of species for which kinetics calculations must be carried out.

As an example of the computational time savings available through use of these techniques, consider a hydrogen air calculation. The basic kinetics package for a hydrocarbon-air system involves sixteen active species, as well as the sub-global reaction incorporated in the quasi-global model and argon. For the hydrogen air system, only ten of these sixteen species are involved; the computational method incorporated in the new program allows the six carbon-containing species to be ignored. Further, the use of element conservation equations allow an additional three species to be removed from the kintics calculation. The net result is the reduction of the number of species involved in the kinetics matrix from sixteen to seven; since the time required to perform a matrix inversion calculation on the computer is proportional to the square of the number of species included in the matrix it is clear that a substantial time savings is involved.

In order to aid in the development of the optimized calculation procedure, computations of the reacting hydrogen-air jet flow studied experimentally by Kent and Bilger [5] have been carried out. This represents an especially difficult chemical kinetics calculations since the reactions in this flow field are near

equilibrium. Results of these calculations are shown in Figure 2., for centerline distributions of the momentum flux ratio $\rho_c U_c^2/\rho_j U_j^2$, temperature, T, and mole fractions of H_2, O_2, H_2O, and NO. The subscript c refers to the centerline value and the subscript j refers to the value at x = 0, i.e., the jet value. Calculations have been carried out to axial distances greater than 160 jet diameters.

No effort has been made to optimize the calculation shown in Figure 2, so that the computed mixing rate of the jet differs substantially from the measured mixing rate in the early part of the jet flow. This in turn has a large effect on the development of the species and temperature profiles, and illustrates the strong coupling between the fluid mechanics and chemical kinetics involved in reacting flow fields. However, with the exception of the NO mole fraction profile, the general character of the distributions shown is reasonably well represented; the divergence of the NO profile from the experimental results requires further study.

CONCLUSIONS AND RECOMMENDATIONS

Substantial progress in the development of a modular model for the dump combustor flow field has been achieved. The major initial step was the development of a model for the directed flow protion of the combustor flow field which combines a sophisticated chemical kinetics scheme, a proved turbulence model, and a versatile numerical approach, and which is optimized to reduce the computational time requirements to the lowest level consistent with an accurate calculation. This has been achieved. As well as providing in itself an important tool for the engineering analysis of reacting flow problems,

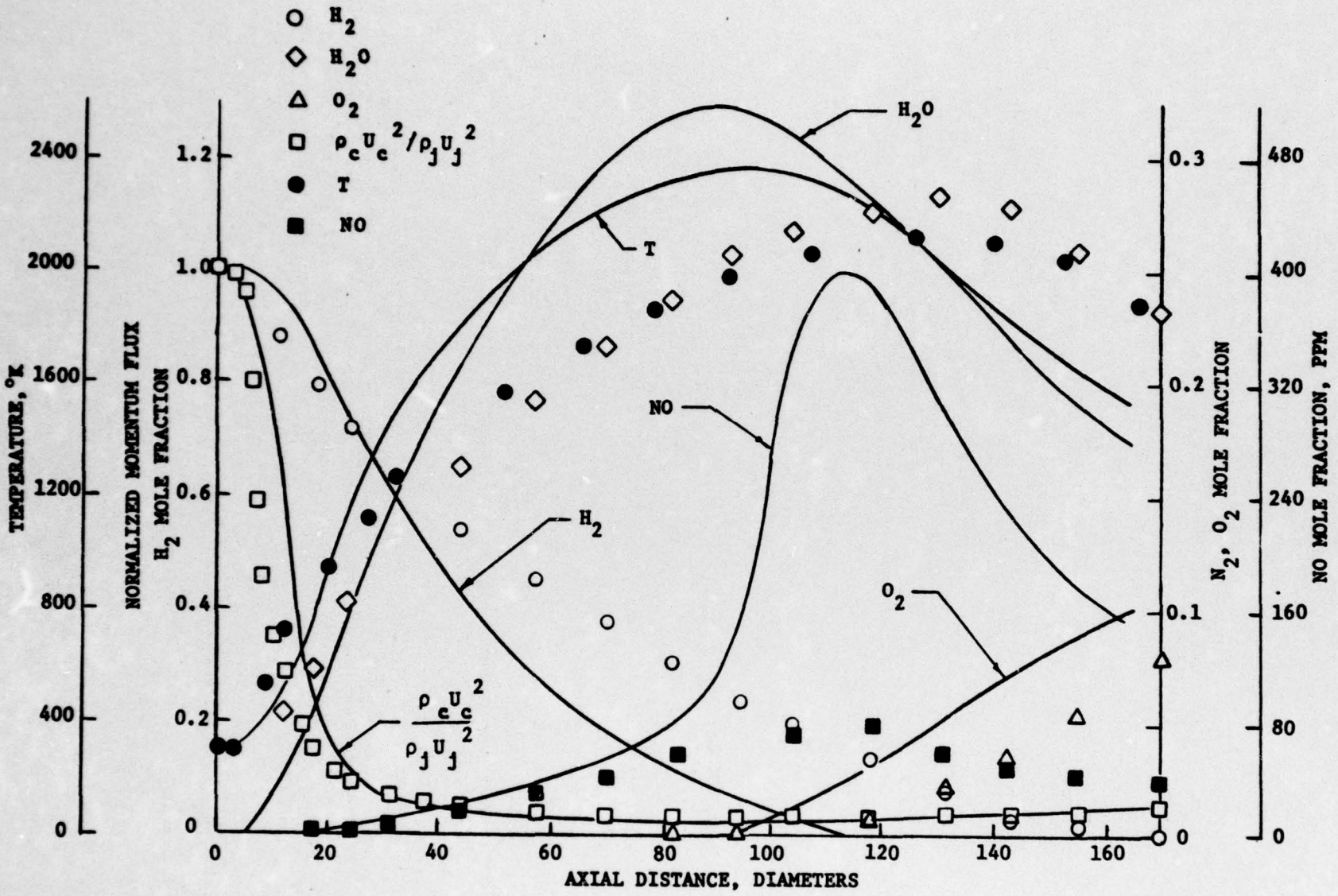


Figure 2. Axial Profiles, Reacting H_2-Air Jet [5]

the parabolic flow model is providing a strong foundation for the dump combustor analysis.

In addition to its utility in a dump combustor analysis, the modular approach will also find application in the analysis of flow behind flame holders. A workshop on flame holders was held as part of the 13th JANNAF Combustion Meeting held at the Naval Postgraduate School 13-19 September 1976. Both solid and liquid fueled ramjet applications were considered. The key point that emerged from this workshop was that the phenomenon involved in the flame holding process are essentially the same as those involved in the basic dump burner application, and that the analytical problems involved are the same as those currently being addressed in the development of the modular model for the dump burner. Thus, the modular approach under development on this program will be expanded to allow the analysis of specific geometries relevant to flame holder problems.

Finally, the analytical work carried out on the development of the modular approach has already resulted in the definition of appropriate dump burner experiments which have been recommended to AFAPL for inclusion in the dump burner experimental program. This interaction with AFAPL will be continued.

While these results represent significant progress, further work is required. Additional studies are needed to adequately characterize reacting, recirculating flows involving fuels ranging from the basic hydrocarbons to the high carbon-to-hydrogen ratio fuels derived from alternate (other than petroleum) sources.

In addition, while the modular concept represents the proper near term approach, a unified multi-dimensional methodology should be developed.

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During this contract period a modular model for the analysis of turbulent reacting flows in dump combustors has been formulated and preliminary calculations have been carried out. The methodology involves coupling a stirred reactor model for the recirculation zone(s) to a parabolic mixing model for the directed flow outside of the recirculation zones. This modular model includes the finite-rate formulations of Edelman and the turbulent kinetic energy turbulence models of Harsha. Elements of the model have been compared with available experimental data and other predictions. The results of the comparison have shown that the

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model is capable of accurate predictions of turbulent reacting flows. Additional work has included the submission of a series of recommended tests to WPAFB/AFAPL. These tests are designed to get data of direct practical use as well as data needed for model development. Steady-state combustion performance and flame stabilization as functions of fuel type, injector location and type, direct injection into the base recirculation zone and inlet flow state are included. Measurements include pressures, temperatures, flow rates, concentrations and thrust as well as direct observation of flame blowout (stabilization). Finally, recommendations for future work have been defined. These include further development of the modular model and the initiation of a unified model. In addition, it is recommended that consideration be given to the impact that the use of alternate (non-petroleum) fuels will have on the combustion characteristics of advanced combustor concepts.